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Nonlinear inelastic behavior of circular concrete-filled steel tubular slender beam-columns with preload effects

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Keywords

concrete, filled, steel, tubular, nonlinear, slender, inelastic, beam, columns, preload, effects, behavior, circular

Disciplines

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Nonlinear Inelastic Behavior of Circular Concrete-Filled Steel Tubular Slender Beam-Columns with Preload Effects

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Abstract

This paper presents a numerical model based on fiber element formulations for simulating the nonlinear inelastic behavior of eccentrically loaded circular concrete-filled steel tubular (CFST) slender beam-columns with preload effects. Deflections caused by preloads are included in the global analysis of CFST slender beam-columns as initial geometric imperfections. Computational algorithms based on the Müller's method are developed to obtain load-deflection responses of CFST slender beam-columns including preload effects. The accuracy of the numerical model is examined by comparisons of computer solutions with experimental results. The numerical model is utilized to investigate the effects of preloads on the axial load-deflection curves, column strength curves and ultimate strengths of circular CFST slender beam-columns under eccentric loading. The numerical model is shown to be accurate and efficient for predicting the behavior of circular CFST slender beam-columns with preload effects. The results obtained indicate that the preload with a ratio of 0.8 might reduce the ultimate axial strength of the CFST slender beam-column by 17.4 %.

1. Introduction

The hollow steel tubes are firstly erected in the construction of a high-rise composite building, followed by the horizontal floors with six to eight storeys before pouring the wet concrete. This construction method induces preloads on the steel tubes, which cause initial stresses and deflections in the steel tubes. These initial stresses and deflections may reduce the stiffness and ultimate strength of concrete-filled steel tubular (CFST) slender beam-columns. Therefore, the effects of preloads must be taken into account in the analysis and design of CFST slender beam-columns.

Experimental and numerical studies on the behavior of CFST columns without preload effects have been conducted by researchers (Neogi *et al*. 1969; Giakoumelis and Lam, 2004; Fujimoto *et al*. 2004; Liang *et al*. 2006). However, research studies on CFST columns with preload effects have been very limited. Zhang *et al*. (1997) undertook tests to examine the effects of preloads on the behavior of eccentrically loaded circular CFST slender beam-columns. Han and Yao (2003) performed experiments on square CFST slender beam-columns under axial or eccentric load and with preload effects. Liew and Xiong (2009)

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studied the experimental behavior of axially loaded circular CFST columns with preloads on the steel tubes. Xiong and Zha (2007) used ABAQUS to investigate the effects of initial stresses on the behavior of eccentrically loaded circular CFST slender beam-columns.

This paper presents nonlinear inelastic analysis and behavior of eccentrically loaded circular CFST slender beam-columns accounting for the effects of preloads and concrete confinements. The theory of nonlinear analyses for CFST slender beam-columns is firstly described. This is followed by verification of the numerical model. The behavior of CFST slender beam-columns with various preload ratios and material and geometric properties is studied using the numerical model.

2. Theory

2.1 Material Models for Steels and Concrete

The steel tube in a circular CFST beam-column is stressed biaxially due to confinement effects. The presence of hoop tension in the steel tube reduces its yield stress in the longitudinal direction. This effect is taken into account in the material constitutive model by an idealized linear-rounded-linear stress-strain curve as shown in Fig. 1(a) presented by Liang (2009). For high strength steels, the rounded part of the curve is replaced with a straight line.

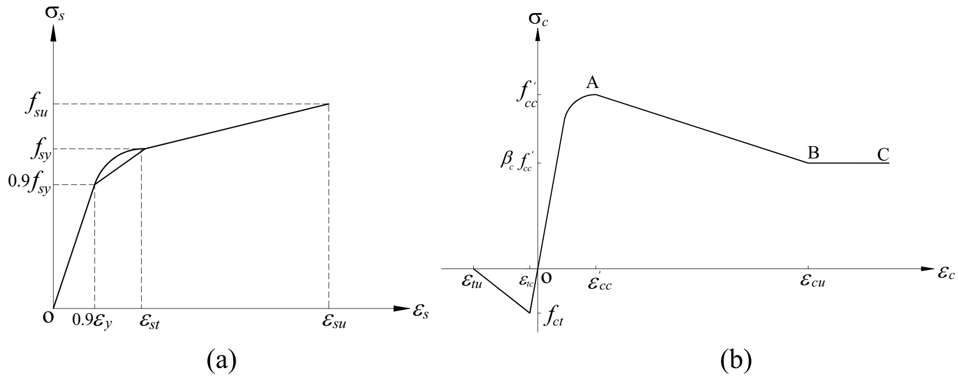

Figure 1: Material models: (a) structural steels (b) concrete

A general stress-strain curve for confined concrete in circular CFST columns shown in Fig. 1(b) is used in the numerical model (Liang, 2011). The part OA of the curve shown in Fig. 1(b) is modeled using the equations suggested by Mander *et al*. (1988) as

$$\sigma_c = \frac{f'_{cc}\lambda\left(\varepsilon_c / \varepsilon'_{cc}\right)}{\lambda - 1 + \left(\varepsilon_c / \varepsilon'_{cc}\right)^{\lambda}} \tag{1}$$

$$\lambda = \frac{E_c}{E_c - \left(f'_{cc} / \varepsilon'_{cc}\right)} \tag{2}$$

where σ_c is the compressive concrete stress, f'_{cc} is the effective compressive strength of confined concrete, ε_c is the concrete compressive strain, ε'_{cc} is the strain at f'_{cc} and E_c is the Young's modulus of concrete (Liang, 2009). The equations proposed by Mander *et al*. (1988) for determining the compressive strength of confined concrete were modified by Liang and Fragomeni (2009) as follows:

$$f'_{cc} = \gamma_c f'_c + k_1 f_{rp} \tag{3}$$

$$\varepsilon_{cc}^{'} = \varepsilon_{c}^{'}\left(1 + k_2 \frac{f_{rp}}{\gamma_c f_c^{'}}\right) \tag{4}$$

where f_{rp} is the lateral confining pressure on the concrete core and k_1 and k_2 are taken as 4.1 and 20.5 respectively. The strain ε'_c is the strain at f'_c of the unconfined concrete and is between 0.002 and 0.003 depending on the compressive concrete strength f'_c and γ_c is the strength reduction factor for concrete proposed by Liang (2009).

Based on the work of Hu *et al*. (2003) and Tang *et al*. (1996), Liang and Fragomeni (2009) proposed a confining pressure model, which is adopted in the present numerical model and is expressed by

$$f_{rp} = \begin{cases} 0.7\left(v_e - v_s\right)\dfrac{2t}{D-2t} f_{sy} & \text{for } \dfrac{D}{t} \le 47 \\ \left(0.006241 - 0.0000357\dfrac{D}{t}\right) f_{sy} & \text{for } 47 < \dfrac{D}{t} \le 150 \end{cases} \tag{5}$$

where D is the outer diameter of the steel tube, t is the thickness of the steel tube, f_{sy} is the steel yield strength and v_e and v_s are the Poisson's ratios of the steel tube with and without concrete infill respectively and they are given by Tang *et al*. (1996).

The parts AB and BC of the stress-strain curve as shown in Fig. 1(b) can be described by

$$\sigma_c = \begin{cases} \beta_c f_{cc}^{'} + \left(\varepsilon_{cu} - \varepsilon_c / \varepsilon_{cu} - \varepsilon_{cc}^{'}\right)\left(f_{cc}^{'} - \beta_c f_{cc}^{'}\right) & \text{for } \varepsilon_{cc}^{'} < \varepsilon_c \le \varepsilon_{cu} \\ \beta_c f_{cc}^{'} & \text{for } \varepsilon_c > \varepsilon_{cu} \end{cases} \tag{6}$$

where ε_{cu} is taken as 0.02 as suggested by Liang and Fragomeni (2009) and β_c is given by Hu *et al*. (2003) as

$$\beta_c = \begin{cases} 1.0 & \text{for } D/t \le 40 \\ 0.0000339\left(D/t\right)^2 - 0.010085\left(D/t\right) + 1.3491 & \text{for } 40 < D/t \le 150 \end{cases} \tag{7}$$

The stress-strain curve for concrete in tension is shown in Fig. 1(b). The tensile strength of concrete is taken as $0.6\sqrt{f'_{cc}}$ while ultimate tensile strain is taken as 10 times of the strain at cracking.

2.2 Analysis of Composite Cross-Sections

The cross-section of a circular CFST beam-column is discretized into fiber elements as depicted in Fig. 2. Fiber stresses are calculated from fiber strains using material uniaxial stress-strain relationships. Axial force and moments acting on a circular CFST beam-column section are determined as stress resultants in the cross-section.

2.3 Load-Deflection Analysis of CFST Slender Beam-Columns

The mid-height deflection of the hollow steel tube under preload can be determined using the load control method. The preload ratio (β_a) is defined as the ratio of the preload acting on the steel tube (P_{pre}) to the ultimate axial strength of the hollow steel tube. The curvature at the mid-height of the CFST beam-column can be obtained as

$$\phi_m = \left(\pi/L\right)^2 u_m \tag{8}$$

where u_m is the mid-height deflection of the CFST beam-column and L is the effective length of the beam-column.

The deflection at the mid-height of the hollow steel tube caused by the preload (u_{mo}) is treated as initial geometric imperfection at the mid-height of the CFST beam-column. The external moment at the mid-height of the CFST beam-columns can be determined as

$$M_{me} = P(e + u_o + u_{mo} + u_m) \tag{9}$$

where P is the applied axial load, e is the eccentricity of the applied load and u_o is the initial geometric imperfection at the mid-height of the hollow steel tube.

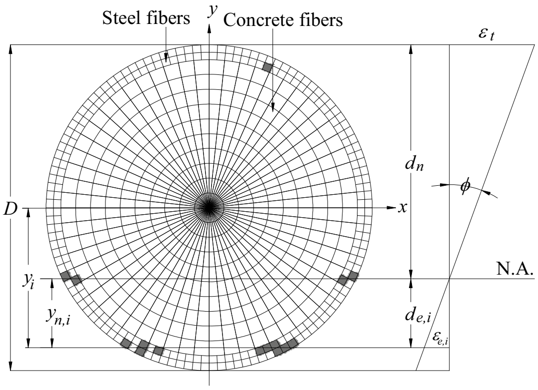

Figure 2: Strain distribution in column section

The analysis procedure is given as follows:

(1) Calculate the deflection u_{mo} of the hollow steel tube under the preload;
(2) Set $u_o = u_o + u_{mo}$;
(3) Initialize the mid-height deflection of the beam-column: $u_m = \Delta u_m$;
(4) Calculate the curvature ϕ_m at the mid-height of the beam-column;
(5) Adjust the neutral axis depth d_n using the Müller's method;
(6) Calculate the force P and moment M;
(7) Repeat Steps (5) to (6) until $|r_m| = |M - M_{me}| < \varepsilon_k$, where ε_k is set to 10^{-4};
(8) Increase the deflection at mid-height of the column by $u_m = u_m + \Delta u_m$;
(9) Repeat Steps (4) to (8) until ultimate load P_u is obtained or deflection limit is reached.

2.4 Müller's Method Algorithms

The Müller's method algorithms are implemented in the fiber element analysis program to adjust the depth of the neutral axis (d_n) in the section to obtain equilibrium conditions. The depth of the neutral axis is adjusted by

$$d_{n,4} = d_{n,3} - \frac{2c_m}{b_m \pm \sqrt{b_m^2 - 4a_m c_m}} \tag{10}$$

$$a_m = \frac{(d_{n,2} - d_{n,3})(r_{m,1} - r_{m,3}) - (d_{n,1} - d_{n,3})(r_{m,2} - r_{m,3})}{(d_{n,1} - d_{n,2})(d_{n,2} - d_{n,3})(d_{n,1} - d_{n,3})} \tag{11}$$

$$b_m = \frac{(d_{n,1} - d_{n,3})^2 (r_{m,2} - r_{m,3}) - (d_{n,2} - d_{n,3})^2 (r_{m,1} - r_{m,3})}{(d_{n,1} - d_{n,2})(d_{n,2} - d_{n,3})(d_{n,1} - d_{n,3})} \tag{12}$$

$$c_m = r_{m,3} \tag{13}$$

The sign of the square root term in the denominator of Eq. (10) is taken to be the same as that of b_m. The values of $d_{n,1}$, $d_{n,2}$ and $d_{n,3}$ and corresponding residual moments r_{m1}, r_{m2} and r_{m3} need to be switched as discussed by Patel *et al*. (2012).

3. Comparisons with Experimental Results

The predicted and experimental ultimate axial strengths of circular CFST columns with preload effects are given in Table 1. Specimens A122, A124, B122, A202 and A204 were tested by Zhang *et al*. (1997) and the remaining specimens shown in Table 1 were conducted by Liew and Xiong (2009). It can be seen from Table 1 that there is a good agreement between predicted and experimental results. The mean value of the predicted to the experimental ultimate axial strength is 0.93. The predicted and experimental load-deflection curves for Specimen A204 are given in Fig. 3. The figure shows that the model predicts well the load-deflection curves of the specimen.

Table 1: Ultimate strengths of circular CFST columns with preload effects

Specimens	D (mm)	t (mm)	L (mm)	u_o (mm)	f_c' (mm)	f_{sy} (MPa)	f_{su} (MPa)	β_a	$P_{u.\exp}$	$P_{u.\mathrm{num}}$	$\frac{P_{u.\mathrm{num}}}{P_{u.exp}}$
A122	133	4.3	1670	L/1000	35.9	325	430	0.22	430	394	0.92
A124	133	4.3	1670	L/1000	35.9	325	430	0.42	416	369	0.89
B122	133	4.3	1670	L/1000	35.9	325	430	0.23	347	346	1.00
A202	133	4.3	2730	L/1000	35.9	325	430	0.22	293	262	0.90
A204	133	4.3	2730	L/1000	35.9	325	430	0.41	282	280	0.99
CFT-I-40-30P	219	6.3	1728	L/1200	44	405	518	0.299	3648	3235	0.89
CFT-I-100-30P	219	6.3	1728	L/1570	113	405	518	0.305	5278	5121	0.97
CFT-I-130-40P	219	6.3	1728	L/4300	139	405	518	0.380	5437	5860	1.08
CFT-L-40-30P	219	6.3	3078	L/2800	49	393	506	0.306	3160	2845	0.90
CFT-L-100-30P	219	6.3	3078	L/2800	111	393	506	0.310	4580	3896	0.85
CFT-L-130-40P	219	6.3	3078	L/1700	125	393	506	0.399	4827	4078	0.84
Mean											0.93
Standard deviation											0.07
Coefficient of variation											0.08

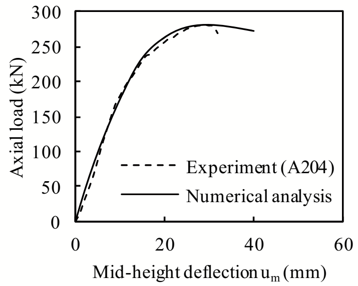

Figure 3: Comparison of predicted and experimental load-deflection curves

4. Behavior

The numerical model developed was used to investigate the behavior of circular CFST slender beam-columns with preload effects. The initial geometric imperfection at the mid-height of the beam-column was taken as $L/1000$. The Young's modulus of steel was 200 GPa. The preload ratios were taken as 0.0, 0.4 and 0.8 in the analysis.

4.1 Effects of Preloads on Load-Deflection Curves

The effects of preloads on the load-deflection curves for a high strength slender steel tube with yield stress of 690 MPa filled with normal strength concrete of 40 MPa were examined. The diameter of the column was 600 mm. The following parameters were considered: the diameter-to-thickness (D/t) ratio of 60, the column slenderness (L/r) ratio of 80 and the loading eccentricity (e/D) ratio of 0.2. Fig. 4(a) shows that increasing the preload ratio significantly reduces the stiffness and ultimate axial strength of the CFST beam-column. The mid-height deflection at the ultimate axial load is found to increase with an increase in the preload ratio. When increasing the preload ratio from 0.0 to 0.4 and 0.8, the ultimate axial strength of the slender beam-column is reduced by 7.7 % and 17.4 % respectively.

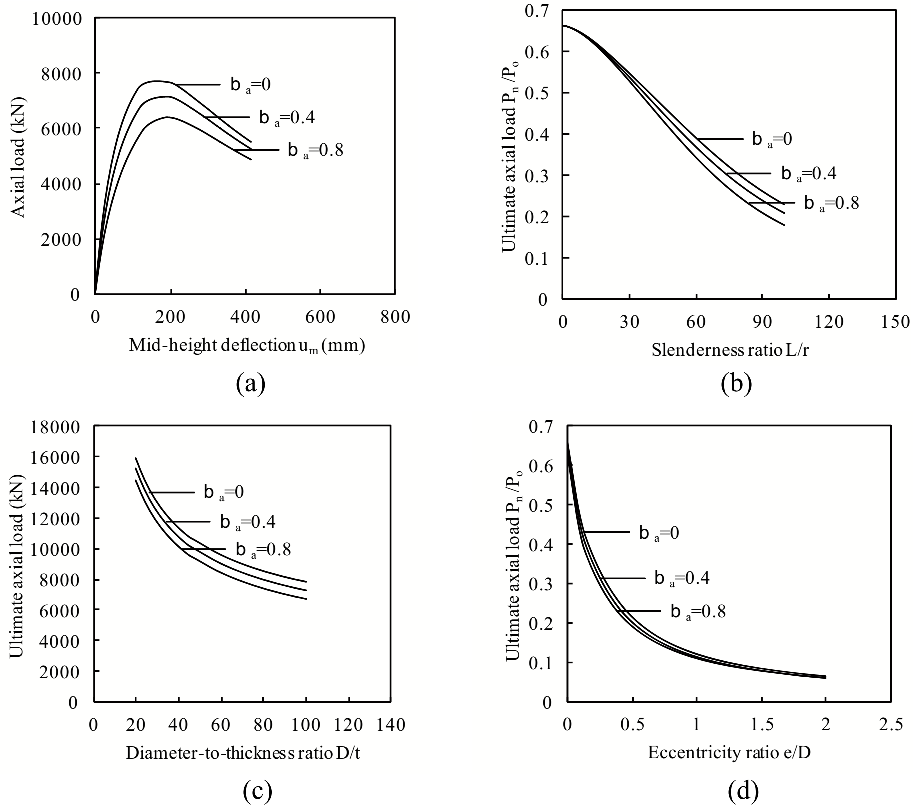

Figure 4: Behavior of circular CFST columns with preload effects

4.2 Effects of Preloads on Column Strength Curves

The analyses of high strength circular CFST beam-columns with a diameter of 500 mm, D/t ratio of 50, L/r ratio varying from 0 to 100, e/D ratio of 0.2, f_{sy} = 690 MPa, f_{su} = 790 MPa and f'_c = 60 MPa were undertaken to study the effects of preloads on the column strength curves. As presented in Fig. 4(b), increasing the L/r ratio significantly reduces the ultimate axial strength of CFST beam-columns with the same preload ratio. The strength ratio tends to increase when increasing the *L/r* ratio. The preload with a ratio of 0.8 might reduce the ultimate axial strength of the CFST slender beam-column with a L/r ratio of 100 by 21.9 %.

The results indicate that when the L/r ratio is less than 22, the preload effect becomes insignificant. This means that for short CFST beam-columns with a L/r ratio less than 22, the preload effect can be ignored in the design.

4.3 Effects of Preloads and Diameter-To-Thickness Ratio

Investigations on the effects of preloads and D/t ratios on the normal strength steel slender tubes with yield stress of 300 MPa filled with high strength concrete of 70 MPa were performed using the numerical model. The diameter of the column section was 700 mm with D/t ratios ranging from 20 to 100. The L/r ratio of 80 and e/D ratio of 0.2 were considered. It can be seen from Fig. 4(c) that the ultimate axial strength decreases with increasing the D/t ratio regardless of the preload value. When the preload ratio increases from 0.0 to 0.4 and 0.8 for the D/t ratio of 100, the ultimate axial strength is decreased by 6.9% and 14.7% respectively.

4.4 Effects of Preloads and Loading Eccentricity Ratio

The numerical studies were carried out to examine the effects of preloads and loading eccentricity ratios on the ultimate strength of normal strength steel slender tube with a diameter of 550 mm filled with normal strength concrete of 40 MPa. The yield stress of the steel tube was 300 MPa. Other parameters used were: $D/t = 55$, $L/r = 80$ and e/D ratio ranging from 0 to 2. It can be observed from Fig. 4(d) that increasing the e/D ratio reduces the ultimate axial strength. The reduction in the ultimate axial strength of CFST columns increases with increasing the e/D ratio from 0.0 to 0.4. However, the strength reduction tends to decrease with an increase in e/D ratio over 0.4. The preloads cause a maximum reduction in the strength of the column with the e/D ratio of 0.4.

5. Conclusions

This paper has presented a numerical model for simulating the behavior of circular CFST slender beam-columns with preload and concrete confinement effects. Computation algorithms have been developed for predicating the load-deflection responses of circular CFST slender beam-columns including preload effects. Verification studies demonstrate that the numerical model is accurate and efficient for the inelastic analysis of circular CFST slender beam-columns subjected to preloads on the steel tubes. The parametric study shows that increasing the preload ratio reduces the ultimate axial strengths of CFST slender beam-columns. The preload effect can be ignored in the design of CFST short beam-columns with the column slenderness ratio less than 22. Increasing the diameter-to-thickness ratio reduces the ultimate axial strength for the same preload ratio. The preload effect is most pronounced when the eccentricity ratio is 0.4.

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